

# Near-nozzle microscopic characterization of diesel spray under cold start conditions with split injection strategy

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# **Near nozzle microscopic characterization of diesel spray under cold start conditions with split injection strategy**

## **Abstract**

Near-nozzle microscopic characteristics of diesel spray under room temperature (25 degC) and low temperature (-2 degC) were investigated by microscopic imaging technique. The primary breakup of winter diesel (WD) and rapeseed methyl ester (RME) sprays were investigated with single and split injection strategies. It was shown that increased viscosity and surface tension under low temperature lead to much poorer dispersion. Under low injection pressure with split injection strategy, the first split injection was unexpectedly severely affected by both temperature and dwell, with significant breakup characteristic differences when dwell varied. By contrast, the second split under low injection pressure tended to be affected only by temperature rather by dwell. High injection pressure considerably alleviated the breakup characteristic difference of the first split injection caused by temperature and dwell although the effects of fuel properties were still seen, leading to better fuel dispersion and more predictable spray characteristics. In addition, RME with higher viscosity and surface tension consistently presented much poorer dispersion quality compared with WD even under high injection pressure where the influence of fuel properties may be insignificant.

**Key words:** spray microscopic characterization, low temperature, split injection strategy

## **1. Introduction**

Fuel temperature is believed to considerably influence the spray behavior because of the varied fuel properties [1]. The processes of injection and spray, for instance, primary breakup and secondary breakup correspondingly change significantly with the variation of fuel temperature, thus the resultant combustion performance. The primary breakup in the near field tends to present great useful information for the study of spray and combustion. More viscous fuels generally lead to smaller effective flow area in the nozzle, higher boundary laminar layer and larger droplets due to the stabilizing effect of the fuel properties [2, 3]. It can be expected that lower temperature makes fuels more viscous and causes larger fuel droplets. More viscous fuels tend to present particles which are more spherical than those with low viscosity because high surface tension enhances the retention of the spherical shape [2]. In [4], however, it was shown that high injection pressure and temperature (1200 K) make the effects of fuel surface tension negligible.

Compared with single injections, multiple injections cause higher IMEP and lower emissions [5, 6]. Dwell interval is an important parameter that governs spray behavior and combustion performance. Shorter dwell leads to stronger spray-combustion interaction [7]. The flame interacting surface between the first split injection and the second split injection increases with shortened dwell. The combustion of the first injection influences that of the second one by changing the temperature and gas compositions [7]. Therefore, shorter dwell results in higher temperature in the middle of the second spray due to raised temperature by the closely coupled first injection. On the other hand, short dwell leads to insufficient oxygen, contributing to insufficient combustion for the second injection. With overlong dwell, the hot gas produced by the combustion of the first split injection cools down, showing little combustion interaction [7].

Engine cold start requires the studies on the unknown primary breakup characteristics under low temperature which are expected to be significantly affected by the variation of fuel properties [8]. Split injection strategy is assumed to significantly impact the spray primary breakup characteristics due to strong interaction between splits. In addition, how the variation of temperature changes the primary breakup features when split injection strategy is employed still requires deep study. To bring more insights on these unknowns, a highly resolved long distance microscope together and an ultrahigh speed CCD camera were used to study the primary breakup of spray during the initial injector opening stage by using both single and split injection strategies.

## **2. Test condition and experimental setup**

For single injection, low injection pressure (60 MPa) and high injection pressure (120 MPa) were used and injection duration was set to 1 ms. When split injection strategy was employed, 60 and 90 MPa injection pressures were used.

Tests were performed under both room temperature (RT, 25 degC) and low temperature (LT, -2 degC) for fuel temperature with ambient temperature kept at RT. Ambient pressure was set to atmospheric condition for all tests. The stability of fuel temperature is of great importance for the success of the tests. An in-house built cooling system (the blue part shown in Figure 1) which kept fuel temperature constant was employed. The mixture of ice and water filled in the pre-cooling barrel was employed to precool the warm pressurized fuel from the common rail. The temperature of ice-water mixture was monitored by a thermocouple installed in the pre-cooling barrel. The temperature of the ice-water mixture ranged from 0 to 1 degC during the tests, keeping nearly constant for up to 5 hours because of the high heat

capacity of water and ice.

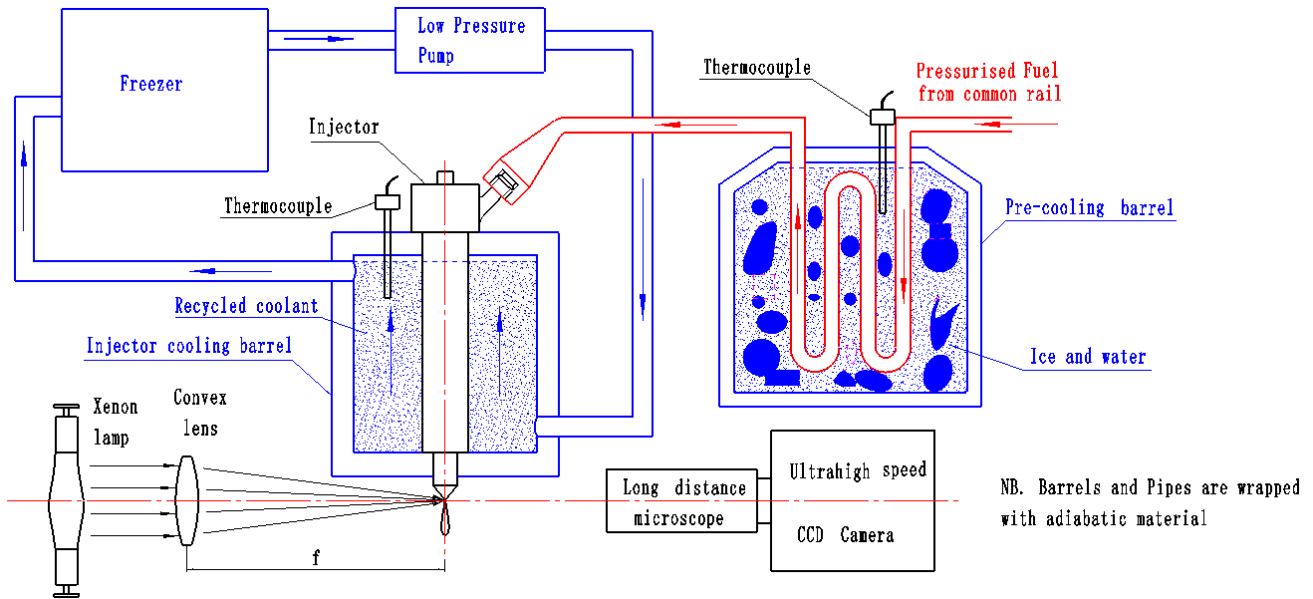


Figure 1. Layout of the experimental setup

To further cool the precooled fuel, another recycle cooling system consisting of an injector cooling barrel, a freezer and a low pressure pump was employed to cool the injector. The injector was installed into the cooling barrel, only leaving injector tip exposed in the air, maximizing the cooling effect for the injector. The lowest stable temperature in the freezer can be as low as -18 degC. The low pressure pump completed with a control module was employed to control the flow rate of the coolant to achieve stable fuel temperature. The temperature of the coolant in the injector cooling barrel is monitored by another thermocouple. Because of the heat transfer between the ambient environment and the recycling coolant, -2 degC is the lowest stable temperature that could be achieved for the coolant in the injector barrel. The temperature of the coolant in the injector cooling barrel generally ranged from -3 to -1 degC. To keep the temperature stable by minimizing heat transfer between the ambient environment and the cooling system, all components (pipes, barrels and low pressure pump) were wrapped with adiabatic material. During the test, if the temperature for the pre-cooling or the temperature for coolant in the injector cooling barrel varied beyond their corresponding values, the test was stopped to allow the coolant to be sufficiently refrigerated. Generally, the superb cooling effect of the cooling system enabled the tests to be carried out for up to 1 hour continuously, achieving high testing condition consistency.

The key components of the imaging setup are the long distance microscope, ultrahigh speed CCD camera, xenon lamp (500 Watts) and convex lens. The frame speed of 1 million fps with corresponding constant resolution of  $312 \times 260 \text{ pixel}^2$  for the camera was employed in this study. The imaging field in

this study is from the injector tip to 2.3 mm downstream. A solenoid driven injector with sharp inlet was used. The diameter of the cylindrical hole of the employed injector is 0.18 mm with length-diameter ratio L/D of 4.4.

### 3. Test fuel

The employed fuels are rapeseed methyl ester (RME) and winter grade pump-grade diesel (WD). It is expected that the spray characteristics considerably depend on two fuel properties, namely viscosity and surface tension which are obtained from experimental measurement, as shown in Figure 2. The varying trends have been published in [10]. It can be seen that viscosity varies exponentially while the surface tension varies linearly. RME tends to be more viscous than WD and the difference is enlarged under low temperature. Considerably higher surface tension for RME than for WD is also observed. The variation of fuel density ( $806 \text{ kg/m}^3$  for WD and  $892 \text{ kg/m}^3$  for RME @  $15 \text{ degC}$ ) is not quantified due to its relatively small variation with temperature [9].

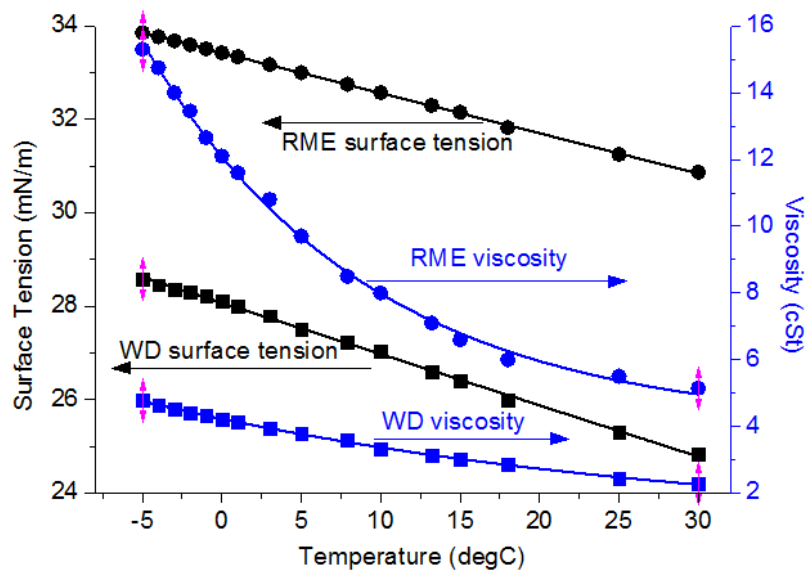


Figure 2. The variation of fuel properties with temperature [10]

### 4. Results

This study mainly focused on the initial injector opening stage when the development of the spray can be captured within the limited view field. The penetration and spray dispersion area were quantified by processing the images with an in-house built Matlab code. The penetration is defined as the farthest point the plume tip reaches (Fig 3 (a)), while the spray area is obtained by summing the area of the pixels the plume occupies in the view field (the area of each pixel is gained by calibration and scaling). Each test was repeated for 15 times to obtain sufficient accuracy. The spray characteristics, namely

penetration and area, show quite small variation under RT. By contrast, under LT, larger variation for penetration and spray area, up to 11 %, is observed. Generally, the overall accuracy and repeatability are satisfying.

#### 4.1 Single injection

Spray at the initial stage showed a special mushroom shaped head which is widely reported in the literature [2], as the one presented for WD with 60 MPa injection pressure in Figure 3(a) where the penetration is defined. The mushroom and neck which is followed by the main spray are typical components for spray during the initial stage. These special shaped parts are generally generated by the residual fuel in the injector and laminar flow regime in the nozzle hole due to the low effective injection pressure when the injector begins to open [2]. The air resistant force is thought to boost the enlargement of the mushroom. By contrast, as presented in Figure 3 (b) the compact liquid pre-jet column was only observed for RME under LT and low injection pressure in present study. The pre-jet is also believed to be related to the residual fuel left by the former injection [2, 12, 13].

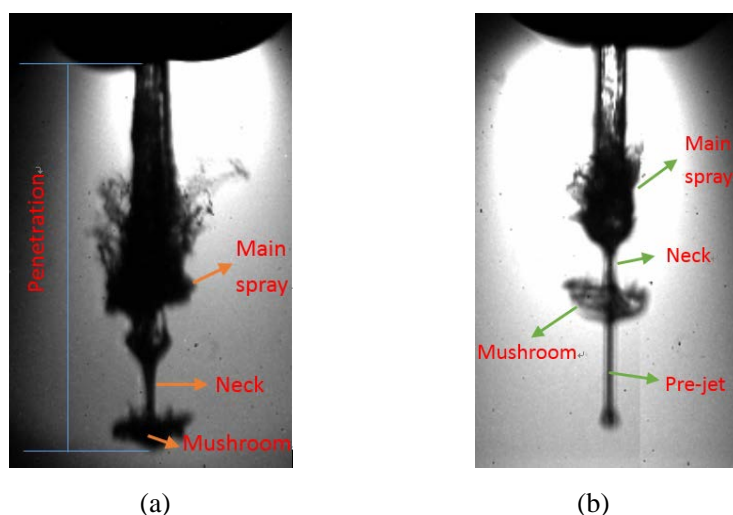


Figure 3. Structure of WD spray (a) and RME spray (b) under 60 MPa and LT

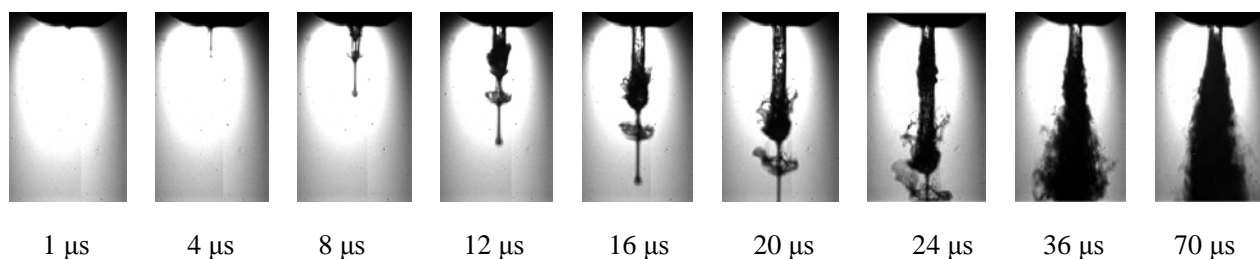
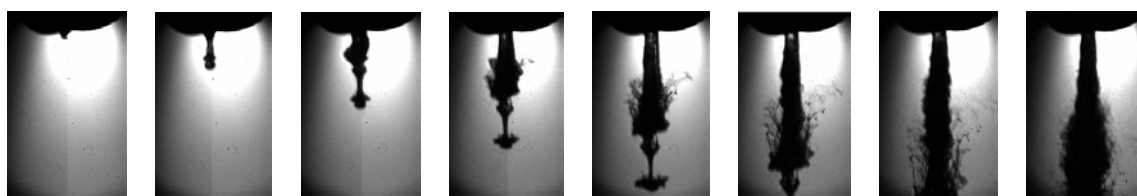


Figure 4. Spray morphology of RME under LT with 60 MPa injection pressure and single injection



1  $\mu$ s      4  $\mu$ s      8  $\mu$ s      12  $\mu$ s      16  $\mu$ s      20  $\mu$ s      24  $\mu$ s      32  $\mu$ s

Figure 5. Spray morphology of WD under LT with 60 MPa injection pressure and single injection

The much lower viscosity and surface tension of WD enable the spray to disperse much better than RME spray. RME spray initially shows smooth intact liquid main spray as shown in Figure 4. Even 70  $\mu$ s after start of injection (ASOI), the compact liquid column was still observable at the very outlet of the nozzle. However, 30  $\mu$ s ASOI, the intact liquid main spray for WD disappeared (Figure 5), meaning almost full atomization. The much better dispersion of WD can be further verified by the dispersed spray area, as presented in Figure 6 (a). WD consistently shows higher area under both low and high injection pressures. The area difference between WD and RME under 120 MPa is still quite obvious. It is believed that the raised injection pressure rather than fuel properties dominates the spray characteristics under high injection pressure, meaning that small area difference between WD and RME should be observed under high injection pressure. The actual results suggest that the influence of fuel temperature on the spray characteristics is very profound even under high injection pressure.

The higher viscosity and surface tension of RME are expected to be responsible for the poorer dispersion. High viscosity leads to high chance of laminar flow, small effective flow area and low effective injection pressure. According to Bernoulli's equation  $u = C_d \sqrt{2\Delta p / \rho}$ , low spray velocity and poor dispersion is expected for RME. The high surface tension of RME (Figure 2) also stabilizes the spray and inhibits the breakup of compact liquid and ligaments. The retaining effect of high surface tension is partly responsible for the poor breakup [2]. It should bear in mind that high density of RME can also attribute to lower effective spray velocity, especially when temperature is decreased.

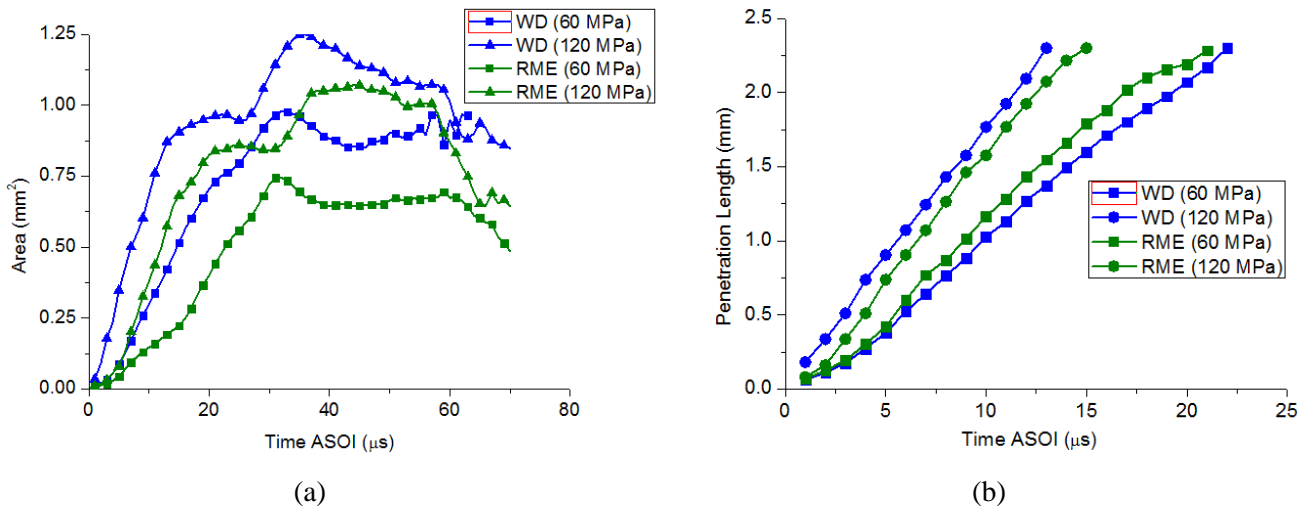


Figure 6. comparison of spray area (a) and penetration (b) between WD and RME under LT

It is surprising to find that RME presents higher penetration than WD under low injection pressure (Figure 6 (b)) although lower penetration for RME under high injection pressure is observed. As

mentioned before, lower velocity of RME tends to show lower penetration and this conflicts with the actual penetration. This abnormal phenomenon can be explained by the formation of mushroom and the pre-jet of the spray at the initial injection stage. As explained in [14], the formation of the mushroom suggests the existence of an acceleration for the residual fuel, namely the mushroom or the pre-jet. The accelerated mushroom head or pre-jet tends to show higher penetration rate than the main spray. In this case, the aforementioned Bernoulli's equation cannot explain the higher penetration rate of RME. Instead, under low injection pressure, 60 MPa in this case, the higher chances of the appearance of mushroom or pre-jet for RME than that of WD caused by higher chances of laminar flow in the nozzle hole seem to be the main reason for the higher penetration for RME. By contrast, under high injection pressure, the hydraulic force is dominant and the plume is well dispersed, resulting in much lower possibility for the appearance of the mushroom head. In this case, the absence of the mushroom head leads to the normal varying trend for penetration.

## 4.2 Split injection

The spray characteristics for split injection strategy are very complicated due to strong interaction between split injections and various involved mechanisms, for instance, fast transition of flow regimes in the nozzle, primary spray collision and induced air driving force [15]. The flow regime transition results in breakup regime transition, and the influence of temperature further complicates the breakup characteristics when split injection employed. The injection characteristics of split injection strategy have been deeply studied in [10], therefore only several typical cases were selected to study the effects of temperature on primary breakup characteristics with split injection strategy. The injection duration was set to  $0.5 \sim \tau \sim 0.5$  ms,  $\tau$  ranging from 0.2 to 0.8 ms.

### 4.2.1 Breakup characteristics under low injection pressure

According to the breakup characteristics with single injection strategy, it can be seen that spray behaves significantly different under different injection pressures. It is necessary to discuss the spray breakup by setting injection pressure to be constant, because the additional parameter, dwell interval, complicates the breakup. In this subsection, the injection pressure was set to 60 MPa.

#### (1) Breakup characteristics of the first split injection for WD spray

As presented in Figure 7, the first split injection under 60 MPa shows distinctive characteristics. The spray characteristics of single injection under RT are employed as references in this study. Under



RT, the first split injections with various dwells show slightly higher dispersed fuel areas with small variation than single injection. Suggested is that the first split injection seems to be almost independent on injection dwell under RT, meaning that the effects of fuel properties and dwell can almost be ignored. By contrast, under LT, dramatic differences between cases with different dwells are clearly shown. The case with 0.2 ms dwell has the largest fuel area, while with dwell of 0.5 ms, the lowest fuel area is seen. An obvious recovery appears when dwell prolongs to 0.8 ms, meaning that the effects of split injection strategy weaken. Besides, it is shown that fuel areas under LT are much lower than those under RT, which can largely be attributed to raised viscosity and surface tension. It is also interesting to find that nearly all cases under LT present a quick area reduction after 60  $\mu$ s ASOI, suggesting the end of injection. Expected is that the first split injection duration under LT is much shorter than that under RT.

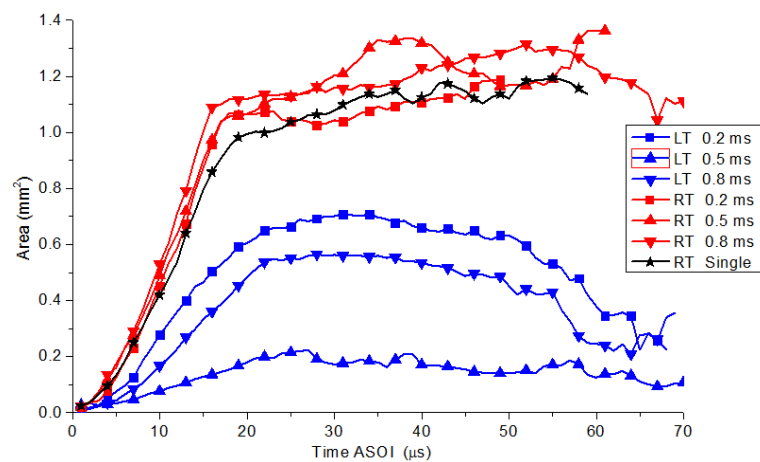


Figure 7. Spray area comparison of the first split injections between RT and LT under 60 MPa (WD)

The corresponding spray penetration length under LT varies significantly as shown in Figure 8. The spray under RT with various dwells penetrates slightly faster than the single injection whereas the spray under LT penetrates much slower than single injection. Apart from that, RT causes nearly linear increase of the plume penetration length, suggesting almost constant velocity for plume. By contrast, LT results in nonlinear increase of penetration length and more importantly a much lower penetration rate after approximate 20  $\mu$ s ASOI. This actually suggests that the injection begins to end, similar to the expected trend from the varying trend of fuel area (Figure 7), although an obvious time disparity in terms of the timing points for the reducing trends is observed from the two graphs. The 0.5 ms dwell case under LT presents the most distinctive spray penetration characteristic, shown in Figure 8. Two nearly linear varying stages are observed, and the penetrating rate is surprisingly much lower than that of counterpart (0.5 ms dwell) and that of single injection under RT.

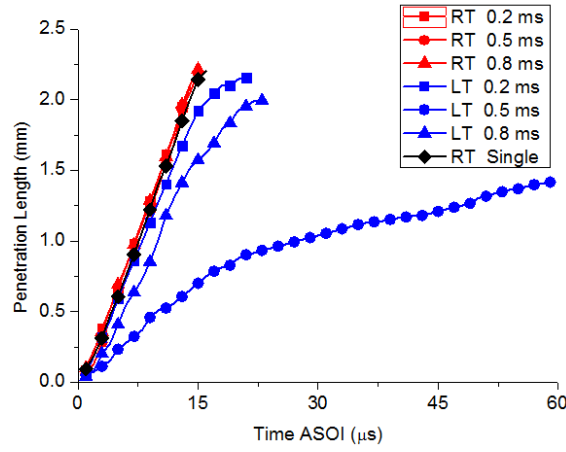


Figure 8. Penetration comparison of the first split injection between RT and LT under 60 MPa (WD)

The spray morphology development for the first split injection with 0.5 ms dwell under RT and LT are shown in Figure 9 and Figure 10 respectively. It can be seen that the spray under RT shows good fuel dispersion and dispersed mushroom is observed. Surprisingly, the plume under LT is actually compact liquid column with intact spheroid head for most of the injection duration. The lower chances of breakup partly due to raised viscosity and surface tension lead to the absence of separated ligaments and droplets, even though the spray shows higher velocity and higher potential of breakup with the rise of needle [2]. At 72  $\mu\text{s}$  ASOI, the end of injection tends to start as the width of the liquid column at the very outlet of the injection obviously reduces, and this leads to the reduction of fuel area, corresponding to the fuel area varying trend presented in Figure 7.

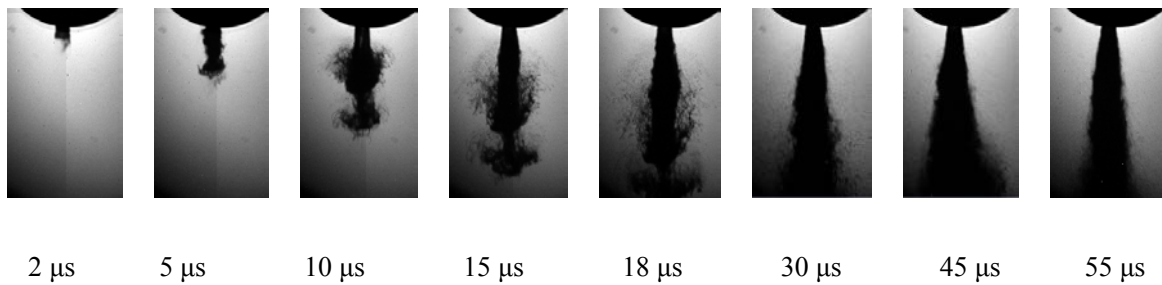


Figure 9. Morphology development of the first split injection with 0.5 ms dwell under RT and 60 MPa (WD)

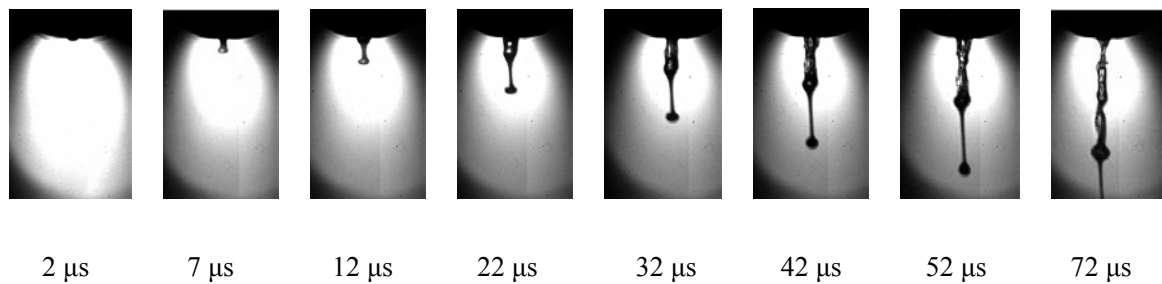


Figure 10. Morphology development of the first split injection with 0.5 ms dwell under LT and 60 MPa (WD)

The first split injection is thought to be independent and its spray characteristics are thought to resemble to the ones of single injection [6, 16]. According to above area developing trends, the first split injection is impacted by both temperature and dwell simultaneously, although under RT the spray characteristics seem to be dominated by the injection pressure and dwell exerts slight influences. The effects of fuel properties are easy to understand through the much lower spray area and much slower penetration under LT. The influences of dwell are quite likely to be attributed to the electric-magnetic characteristics of the injector [17]. The employed injector in this study is a solenoid injector, and the strong interaction between a train of closely coupled energizing signals and the electrically induced resistance tend to significantly affect the needle lift and the effective injection duration. Although how the movement of the needle is impacted by this interaction is unknown, the effective injection duration seems to be shortened. The shortened injection duration means lower needle lift, lower effective injection pressure (due to throttling effect [10]) and the resultant weaker effect of hydraulic force. The relative weak effect of injection pressure and the relative strong effect of fuel properties make the spray characteristics more unpredictable.

Kouros [17] studied the mass flow rate (MFR) of split injection with a long tube measuring instrument and it was reported that the first split injection showed 19% of less injected fuel than single injection. Although the reason was not given, it is suggested that the actual injection duration of the first split injection can be considerably influenced by split injection strategy with various dwells. It should also be noted that the increased viscosity deteriorates the effective injection duration by decelerating the needle motion and increasing the hydraulic energy loss of fuel in the nozzle hole.

When RME was employed, the very high viscosity lead to a very small amount of fuel injected, and it is difficult to characterize the spray. The first spray of RME under 60 MPa is therefore not discussed in this study.

## (2) Breakup characteristics of the second split for WD

The second split injection tends to show some different spray characteristics because the behavior of the first split injection can affect the development of the second split injection (the so called interaction). The area development under both RT and LT with a wide range of dwells is shown in Figure 11. Similar varying trends and comparable plume areas for the cases with various dwells under LT are observed. This suggests the dwell slightly affects the second split injection, namely, the second split injection is independent on the interaction between splits. By contrast, the plume under RT seems to be

strongly impacted by the interaction. It is worth noting that LT cases have much smaller areas than the RT cases when the fuel areas reach the stable stage.

Raised fuel viscosity under LT can severely shorten the effective injection duration for each split injection, as discussed for the aforementioned first split injection. This means that split injections energized by a train of closely coupled energizations become more independent and separated under LT, resulting in longer actual dwell intervals between split injections compared with the cases under RT. The interaction between split injections under LT is significantly weakened and the second split injections are not obviously influenced by the first split injections. The split injections with various dwells are expected to demonstrate similar breakup characteristics under LT.

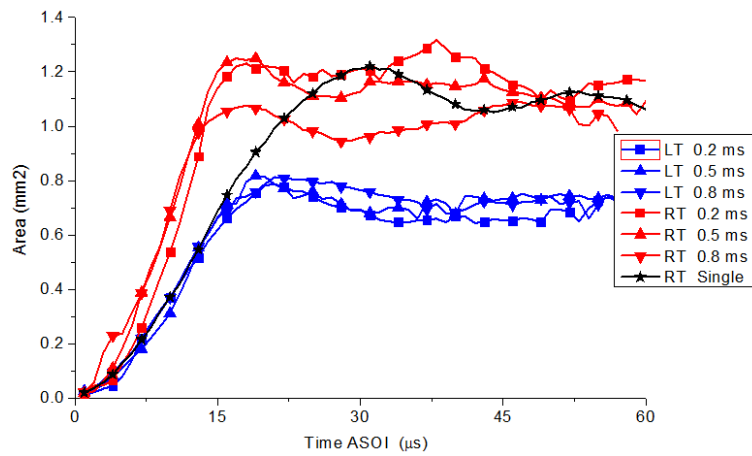


Figure 11. Spray area comparison of the second split injection between RT and LT under 60 MPa

The second split injections under RT are found to be severely affected by the duration of dwell, and are thought to be simultaneously impacted by three mechanisms, namely, primary collision, spray induced air driving force and lower MFR [6, 17]. The tip of second split injection tends to collide with the tail of the first split injection when dwell is short, causing the deceleration of the second split injection but the increase of fuel area. This is so called primary collision. Ambient gas near the injector tip is likely to be driven forward by the motion of the first split injection plume, leading to smaller drag force for the second split injection. The MFR may be lower at the initial spray stage of the second split injection due to the oscillation and stagnation of the needle motion probably caused by the electric-magnetic characteristics of the injector or radial movement of needle [17]. When dwell varies, the influencing factors for the second split injection are different and different breakup characteristics are observed.

Given the three mechanisms presented above, it can be expected that air induced driving force is

important for all cases under RT. However, collision may be more obvious for 0.2 ms dwell case. This can be verified by the corresponding varying trends of penetration for these cases (Figure 12). The plume under RT penetrates faster than the single injection. On the other hand, the plume of all cases under LT penetrates obviously lower than the single injection. The area developing trend and morphology development of the first split injection under LT (shown in Figure 11 and Figure 13 respectively) suggest that the air induced driving force can be ignored and the collision is unlikely to occur. Therefore, features of the second split injection tend to be governed by fuel properties (viscosity and surface tension), penetrating apparently slower than single injection under RT.

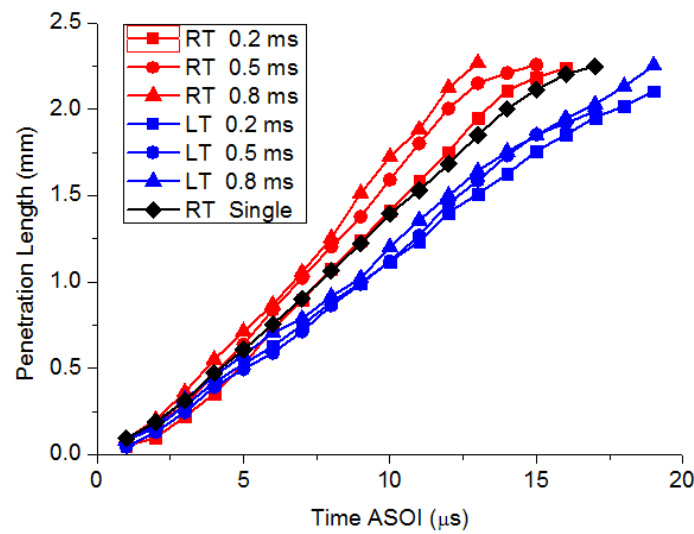


Figure 12. Penetration comparison of the second split injection between RT and LT under 60 MPa (WD)

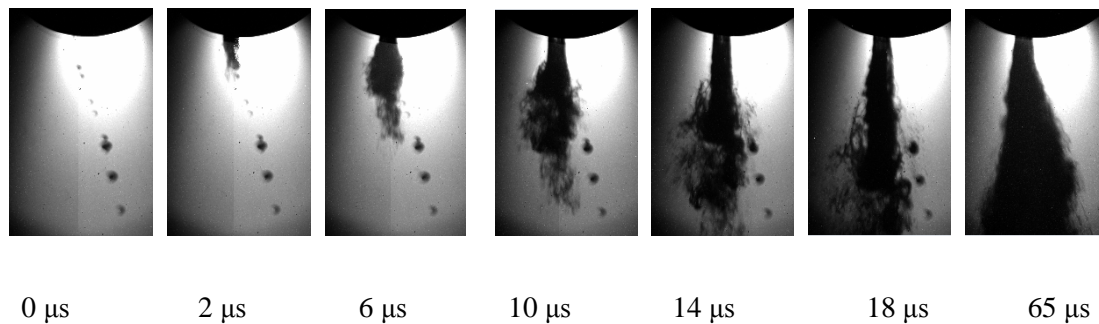


Figure 13. Spray morphology of the 2<sup>nd</sup> injection with 0.2 ms dwell under 60 MPa and LT (WD)

### (3) Spray characteristic comparison between RME spray and WD spray

The second split injection of RME shows comparable characteristics to those of WD with short dwells (Figure 14 (a)). Specifically, when dwell are set to 0.2 and 0.5 ms, RME spray shows similar spray area to WD spray. However, when dwell is set to 0.8 ms, RME presents obviously lower spray area. Although the high viscosity of RME inhibits the first spray as mentioned before, the

advanced injector opening for the second split injection considerably boosts the spray dispersion due to higher effective injection pressure. With the rise of dwell, the interaction between split injections weakens significantly and the injector opening for the second split injection cannot be advanced considerably. This means that the spray dispersion cannot be enhanced by higher effective injection pressure related to the higher injector opening. It is interesting to note that the penetration of RME is slightly lower than WD, and this trend is different from that when single injection strategy is employed, as shown in Figure 14 (b). The higher viscosity of RME is believed to be the reason for the lower penetration rate.

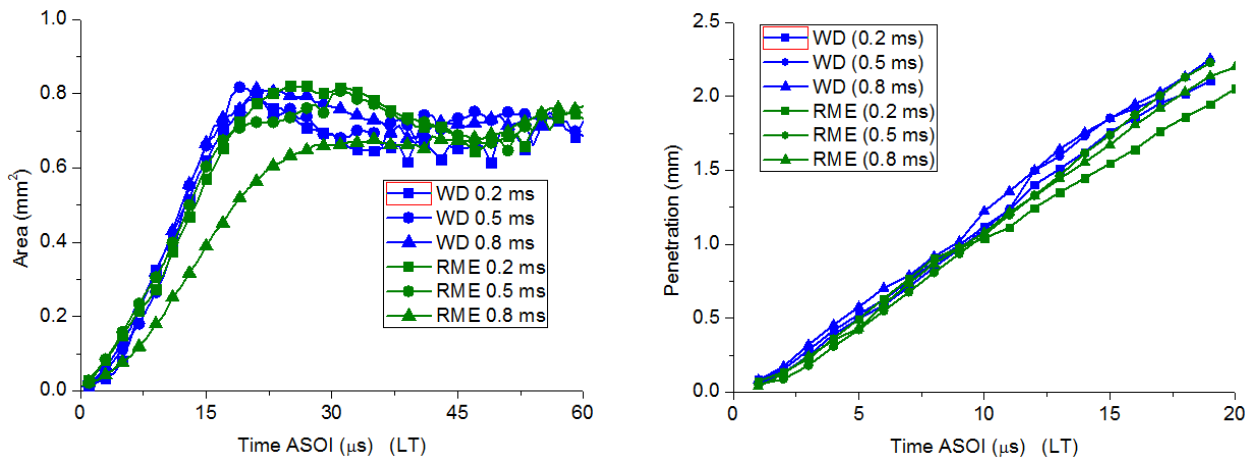


Figure 14. Comparison of spray area (a) and penetration (b) for the 2<sup>nd</sup> injection between RME and WD under 60 MPa

The effect of fuel properties on the spray dispersion is quite obvious. As shown in Figure 15, the droplets at the tail of the first injection for RME are spherical and tend to be very stable. The high surface tension of RME enables the droplets to retain the spherical shape although the air drag force may be strong. By contrast, the droplets for WD (Figure 13) are more likely to break up.

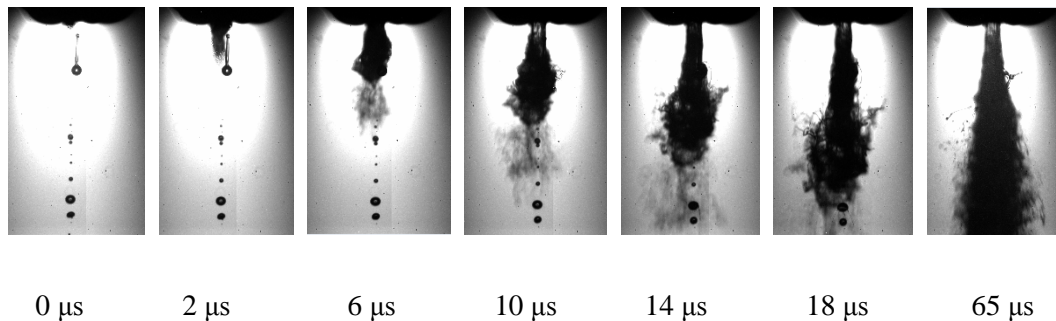


Figure 15. Morphology of the 2<sup>nd</sup> injection with 0.2 ms dwell under 60 MPa and LT (RME)

#### 4.2.2 Breakup characteristics under high injection pressure

High injection pressure may lead to different injection characteristics as the hydraulic force becomes

the dominant factor. In this subsection, the injection pressure is set to 90 MPa.

#### (1) Breakup characteristics of the first split injection for WD

The first split injection behaves in a different way under high injection pressure, especially under LT, when compared with the one under low injection pressure. The areas for cases with different dwells under RT develop consistently with single injection and little differences between cases are observed (Figure 16). This suggests that the first split injection is not obviously affected by the fuel properties or the dwell interval. Under LT, although some different characteristics for cases with various dwells can be found, similar varying trends and comparable areas are shown. It is noteworthy that the differences between LT and single injection are much smaller than those under low injection pressure (60 MPa, Figure 7). The above description shows that under high injection pressure, the effects of fuel properties are greatly weakened by the hydraulic force, contributing to more predictable spray characteristics. The impact of short dwell is also considerably dampened by the dominant hydraulic force. More importantly, two LT cases (dwell of 0.2 and 0.5 ms) tend to show higher areas than the RT cases for the initial spray stage (approximate before 10  $\mu$ s). In addition, for the stable stage, although an obviously hump is observed for all cases, the LT cases show the hump later than the cases under RT with apparently larger magnitudes. The throttling effects and needle oscillation tend to be responsible for the formation of the hump. The larger hump magnitudes for LT case again suggests that during the injector opening stage, LT leads to stronger throttling effects with longer duration [10].

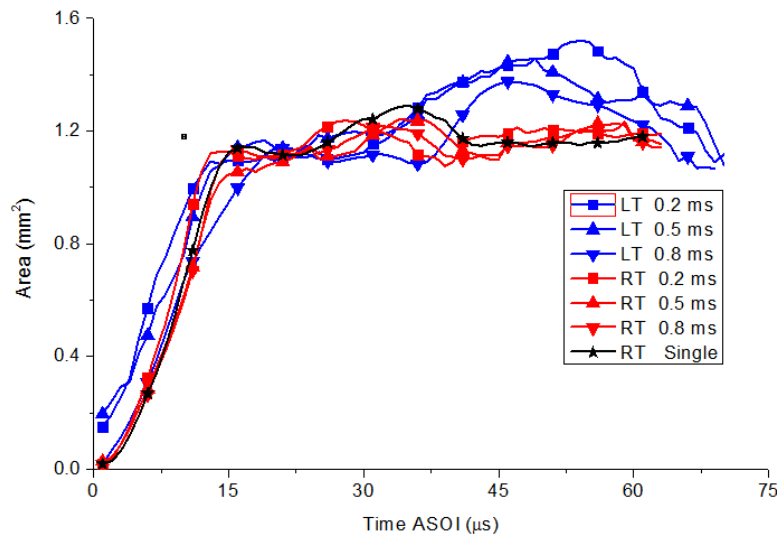


Figure 16. Spray area comparison of the first split injection between RT and LT under 90 MPa

The penetration length of the first split injection under LT for all cases tends to be obviously higher than that under RT (Figure 17). The aforementioned formation of the accelerated mushroom is assumed

to be the root reason for the higher penetration rate under LT than RT. This quicker penetration rate under LT leads to higher fuel area for the initial spray stage shown in Figure 16. It is suggested again that LT has higher possibility of formation of mushroom and stem. This can be confirmed by the spray morphology under RT and LT shown in Figures 18 and 19. It can be seen that the mushroom shaped head under LT is prominent while under RT no such spray morphology is seen. In addition, the LT cases show more obviously nonlinear varying trend than RT cases, and the penetration difference between LT cases with a wide range of dwells is more obvious, meaning that the influences of fuel properties and dwell interval are still observable although significantly weakened by hydraulic force.

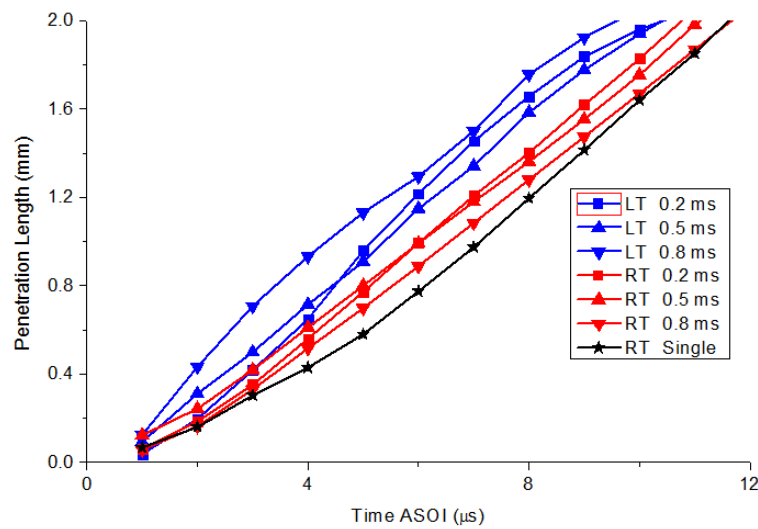


Figure 17. Penetration comparison of the first split injection between RT and LT under 90 MPa (WD)

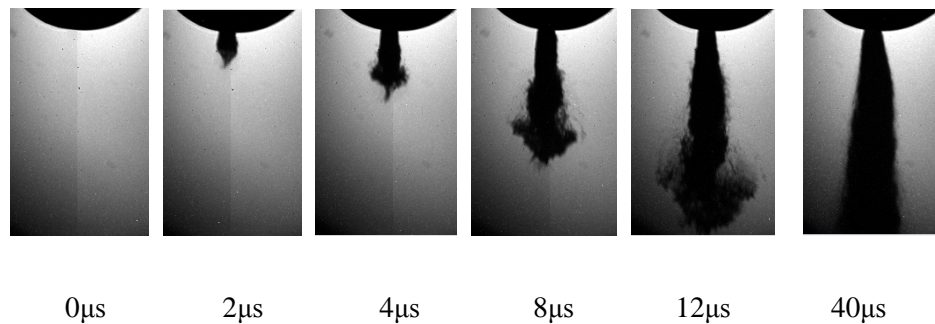


Figure 18. Spray morphology of the first split injection with 0.2 ms dwell under RT and 90 MPa (WD)

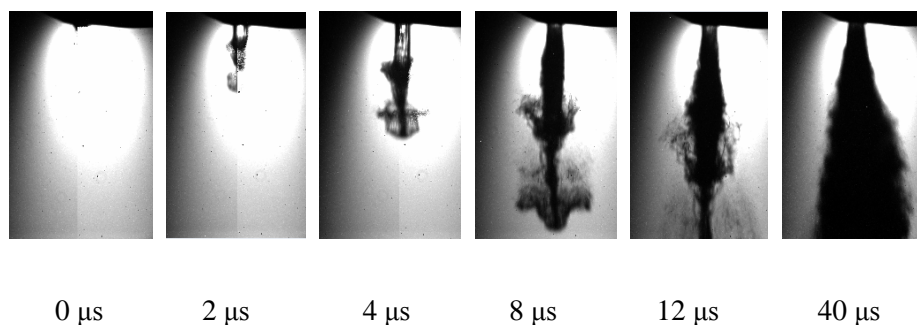




Figure 19. Spray morphology of the first split injection with 0.2 ms dwell under LT and 90 MPa (WD)

## (2) Breakup characteristics of the second split injection for WD

Fuel area for the second split injection under RT (Figure 20) shows similar developing trend to single injection but with higher increasing rate during the initial spray stage. The higher initial increasing rate is probably attributed to two probable given reasons, induced air driving force and primary collision. The air driving force caused by the first split injection tends to be strong under high injection pressure as the plume of the first split injection can be fully dispersed and push massive gas forward, thus strong driving force for the second split injection. The primary collision between the end of the first split injection and the tip of the second split injection also tends to be strong under higher injection pressure. The injector closing can be obviously retarded by the raised injection pressure, and the actual dwell interval between two consecutive split injections is shortened [10]. More fuel of the tail of the first split injection is chased and collided by the tip of the second split injection.

Several area varying stages similar to single injection are clearly shown. It is interesting to find that the second split under LT case similarly shows larger fuel area than single injection, even slightly larger than that of the second split injection under RT during the fuel area rising stage. Expected is that the air driving force under LT may be almost as strong as that under RT because under high injection pressure, the hydraulic force is dominant. It should be mentioned that the collision under LT should be actually weaker as the raised viscosity weakens the interaction. Therefore, higher penetration and quicker breakup of the mushroom is more likely to cause the higher fuel area. In addition, the observably lower area for the stable stage under LT means poorer breakup due to raised particle stability.

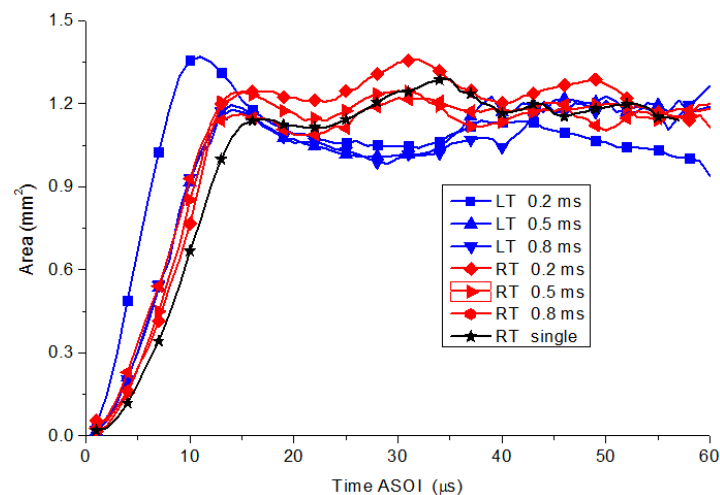


Figure 20. Spray area comparison of the second split injection between RT and LT under 90 MPa

Similar to the first split injection, the second split injection under LT penetrates obviously faster than single injection and the second split injection under RT (Figure 21). Weaker primary collision may be responsible. The more nonlinear varying trend for LT cases illustrates that the effects of fuel properties still cannot be ignored. It is noteworthy that RT cases show obvious nonlinear increasing trends during the first few microseconds, meaning strong fuel collision. By contrast, an obvious increasing trend is seen for LT cases, and it is expected that collision under LT is not actually as strong as that under RT.

According to these results, split injection strategy tends to simultaneously influence both the first and second split injections by combination of dwell and the variation of the dominate factors (fuel properties and hydraulic force). Although the combining influences of the injection strategy and fuel properties caused by the variation of temperature can be significantly damped by the rise of injection pressure, the effects of fuel properties are strong.

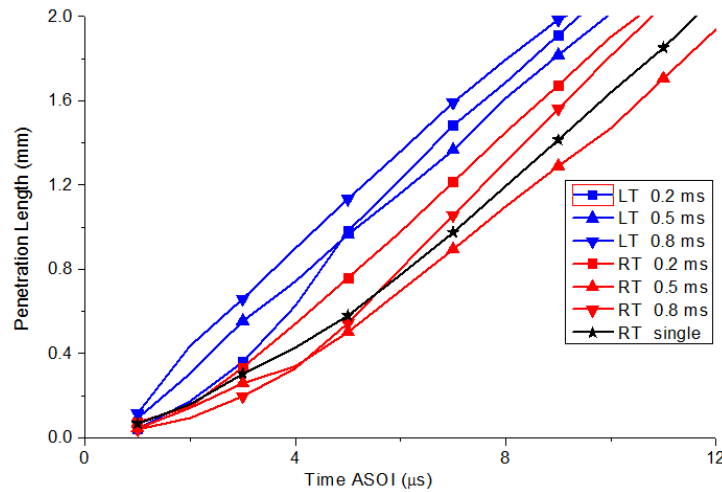


Figure 21. Penetration comparison of the second split injection between RT and LT under 90 MPa

### (3) Breakup comparison between RME spray and WD spray

Similar to single injection, the use of split injection strategy fails to enable the RME spray disperse as well as WD spray under high injection pressure, as shown in Figure 22 (a). The hydraulic force is insufficiently strong to overcome the strong viscous force of RME under LT. The strong surface tension also significantly inhibits the breakup of ligaments and large droplets. The spray morphologies for RME (Figure 23) and WD (Figure 24) present huge difference in terms of dispersion quality. Much slower penetration for RME is observed with various dwells due to lower velocity (Figure 22 (b)).

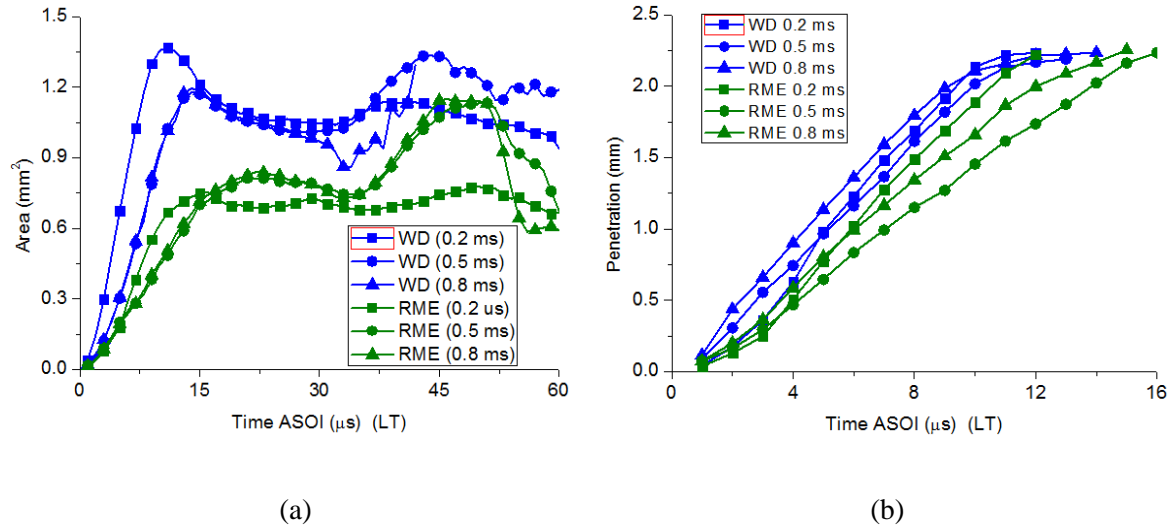


Figure 22. Comparison of spray area (a) and penetration (b) for the 2<sup>nd</sup> injection between RME and WD under 90 MPa

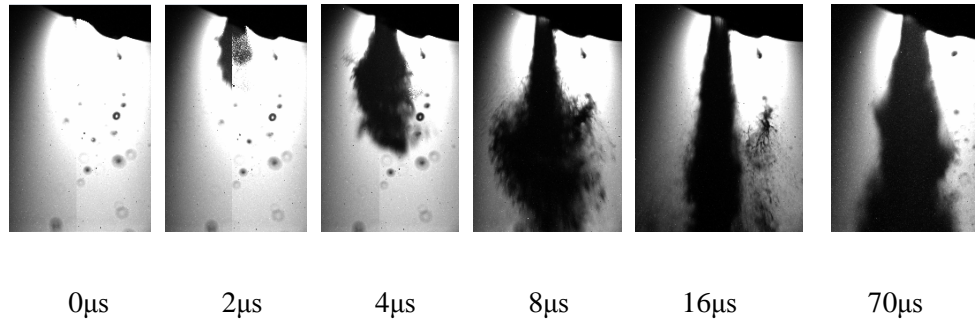


Figure 23. Spray morphology of the 2<sup>nd</sup> split injection with 0.2 ms dwell under LT and 90 MPa (WD)

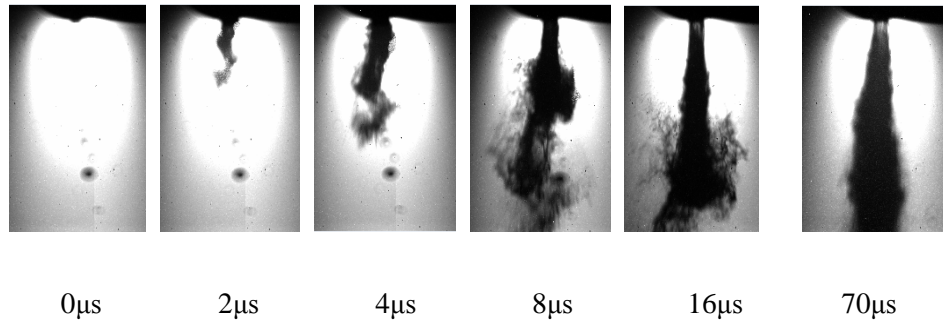


Figure 24. Spray morphology of the 2<sup>nd</sup> split injection with 0.2 ms dwell under LT and 90 MPa (RME)

## Conclusion

Study on primary breakup of diesel spray can significantly enhance the understanding of spray and combustion. The spray primary breakup was studied by the characterization of plume morphology development. Tests were carried out under both room temperature and cold start condition with single and split injection strategies. The following conclusions can be drawn.

The effects of changed fuel properties due to LT apparently inhibit the spray primary breakup, leading to large ligaments, even compact liquid column. Although raised injection pressure leads to

much better spray dispersion, the spray behavior is still observably impacted by LT.

The primary breakup is further complicated by the employment of split injection strategy. Under LT, the first split injection which is expected to be independent on split injection interaction is severely affected by the variation of dwell and fuel properties. The rise of injection pressure can effectively weaken these influences. Under RT, characteristics of the second split injection vary significantly with the change of dwell because of strong interaction. LT effectively reduces the variation of breakup characteristics of the second split injection by significantly weakening the interaction, although poorer breakup occurs due to raised viscosity and surface tension.

Bio-fuel, RME, shows much poorer dispersion under cold condition due to considerably raised viscosity and surface tension. High injection pressure (less than 120 MPa) cannot effectively improve the dispersion quality. Much higher injection pressure is required to obtain favorable spray under low temperature.

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